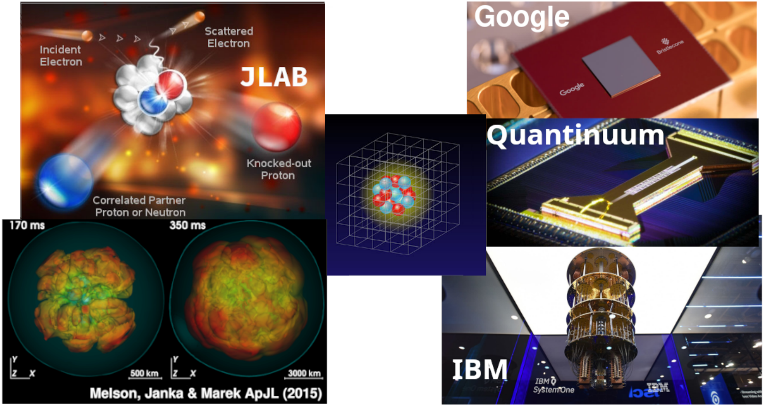
Nuclear dynamics on digital quantum computers

Alessandro Roggero

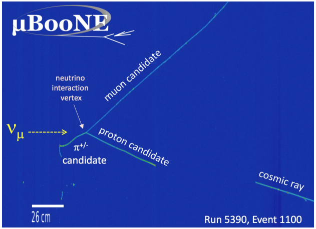


TIFPA
Trento Institute for
Fundamental Physics
and Applications

Zakopane Conference on
Nuclear Physics

– 01 September, 2026 –

Nuclear cross sections in neutrino oscillation experiments



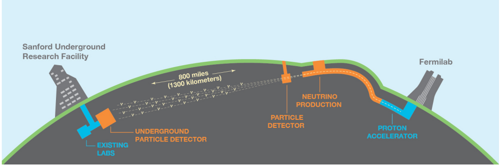
Goals for ν oscillation exp.

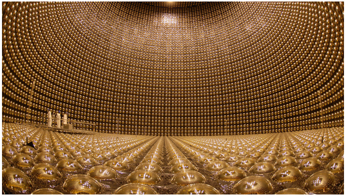
- neutrino masses
- accurate mixing angles
- CP violating phase

$$P(\nu_\alpha \to \nu_\alpha) = 1 - sin^2(2\theta) sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

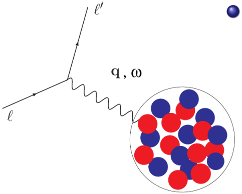
- need to use measured reaction products to constrain E_ν of the event

DUNE, MiniBooNE, T2K, Minerνa, NOνA,...





Inclusive cross section and the response function



- xsection completely determined by response function

$$R_O(\omega) = \sum_f \left|\langle f|\hat{O}|\Psi_0\rangle\right|^2 \delta\left(\omega - E_f + E_0\right)$$

  - excitation operator $\hat{O}$ specifies the vertex

Extremely challenging classically for strongly correlated quantum systems

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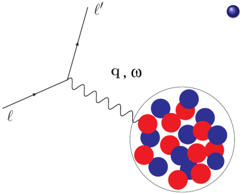

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Extremely challenging classically for strongly correlated quantum systems

Ground state calculations are simpler, can we use them instead?

$$R_O(\omega) = \langle\Psi_0|\hat{O}^\dagger\delta\left(\omega - \hat{H} + E_0\right)\hat{O}|\Psi_0\rangle$$

Ground state expectation value but the δ is too singular to use directly

- we can use instead an approximation to the delta function with some finite width (Lorentzian, Gaussian, ...)
- experiments have an intrinsic energy resolution anyway

The response function on a quantum computer

Quantum Computers are good at time-evolution, can we leverage that?

$$\begin{aligned}\delta\left(\omega-\hat{H}+E_0\right)&=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}dt\exp\left(it\left(\omega-\hat{H}+E_0\right)\right)\\&\approx\frac{1}{\sqrt{2\pi}}\int_{-T}^{T}dt\exp\left(it\left(\omega-\hat{H}+E_0\right)\right)\end{aligned}$$

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Quantum Computers are good at time-evolution, can we leverage that?

$$\delta\left(\omega - \hat{H} + E_0\right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt \exp\left(it\left(\omega - \hat{H} + E_0\right)\right)$$
$$\approx \frac{1}{\sqrt{2\pi}} \int_{-T}^{T} dt \exp\left(it\left(\omega - \hat{H} + E_0\right)\right)$$

But then we "only" need to calculate a real-time correlation function

$$C_O(t) = \langle\Psi_0|\hat{O}^\dagger \exp\left(-it\left(\hat{H} - E_0\right)\right)\hat{O}|\Psi_0\rangle$$
$$= \langle\Psi_0|\hat{O}^\dagger(t)\hat{O}(0)|\Psi_0\rangle$$

for a maximum time of roughly $T \approx 1/\Delta\omega$ for some fixed resolution $\Delta\omega$.

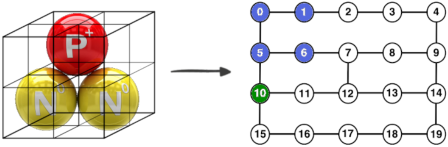
Second step above correct only for exact eigenstates $\hat{H}|\Psi_0\rangle = E_0|\Psi_0\rangle$.
Need to be careful if we can only approximate initial state.

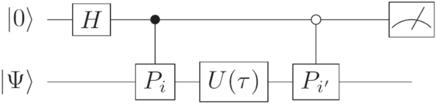
Real time correlators on current generation devices

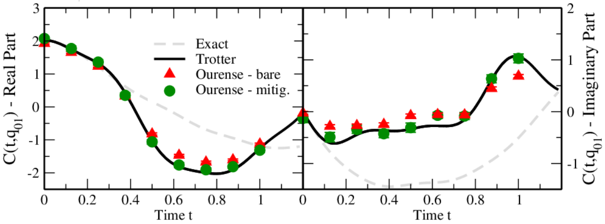
- First steps toward nuclear response: real-time correlators

$$R(\omega) = \int dt e^{i\omega t} C(t) \quad \text{with} \quad C(t) = \langle \Psi_0 | O(t) O(0) | \Psi_0 \rangle$$

- Can be done "easily" using one additional qubit (Somma et al. (2001))







Baroni, Carlson, Gupta, Li, Perdue, AR PRD(2022)

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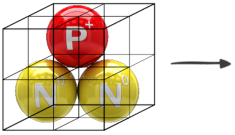

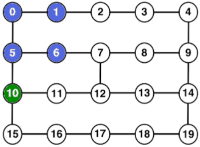

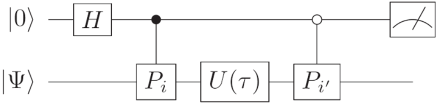

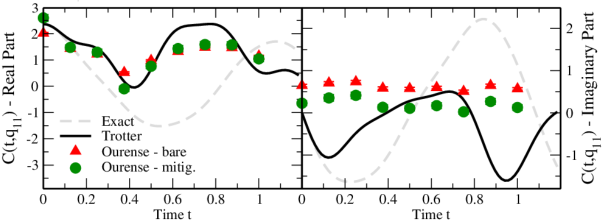

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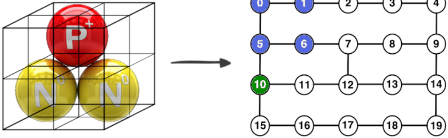

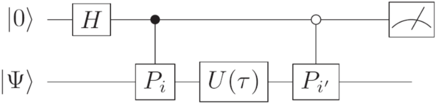

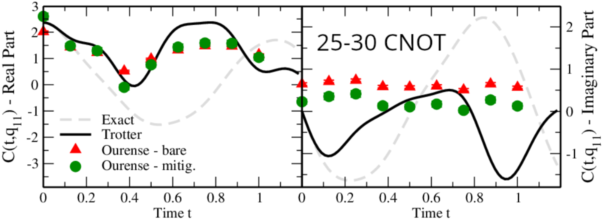

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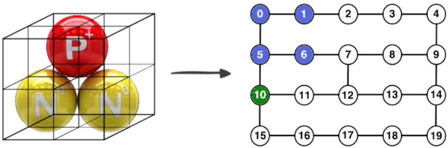
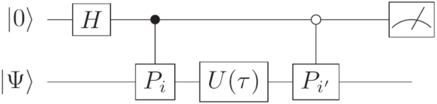
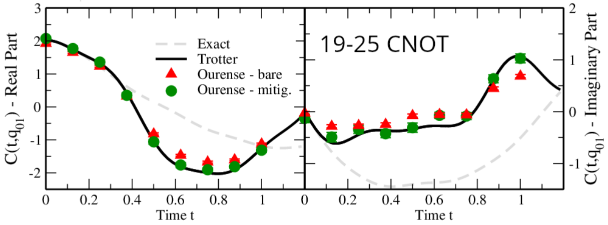
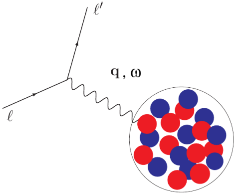






Baroni, Carlson, Gupta, Li, Perdue, AR PRD(2022)

Towards exclusive scattering using quantum computing



- response $R(\omega) \Leftrightarrow$ probability for events at fixed ω
- exclusive x-sec $\rightarrow$ events with specific final states

IDEA: prepare the following state on QC

$$|\Phi\rangle = \sum_\omega \sqrt{R(\omega)}\,|\omega\rangle \otimes |\psi_\omega\rangle$$

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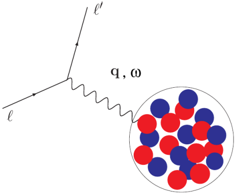

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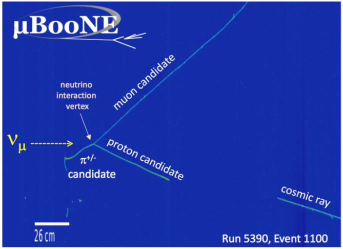
- after measurement, the second register contains final states at ω!

Blume-Kohout et al. (2013)



AR & Carlson PRC(2019)

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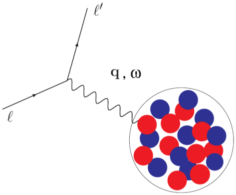

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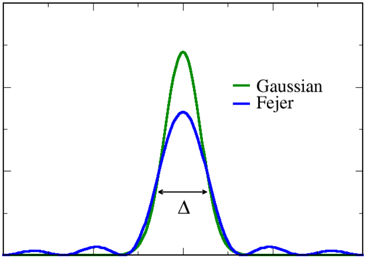
with R_Δ is a smeared response with energy resolution Δ



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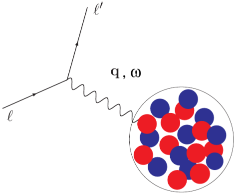

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How expensive is this going to be?

- 4000 qubits – 10^{11} gates[1]
- 6000 qubits – 10^{9} gates[2]
- 500 qubits – 10^{7} gates[3]

[1]Roggero et.al (2020) [2]Watson et.al (2023)

[3]Spagnoli, Roggero, Lissoni (2025)

Quantum Computing in 2026: where are we?

Where we would like to be

slide idea from A.Baldazzi's talk @ TIQIT'26

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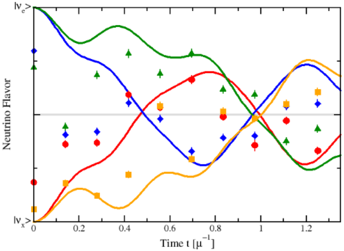
N=4 on IBM (2021)



B.Hall et al. PRD(2021)

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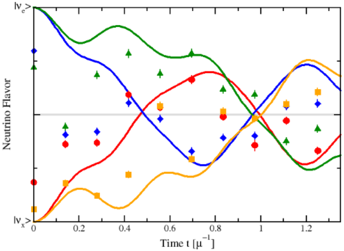

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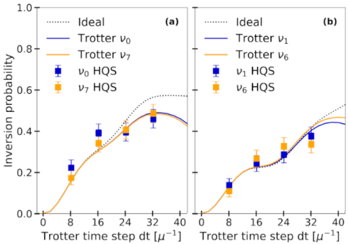
N=8 on Quantinuum (2023)



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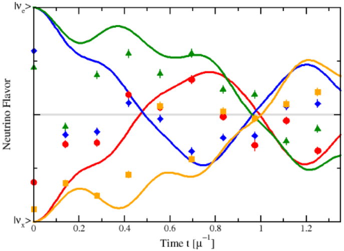

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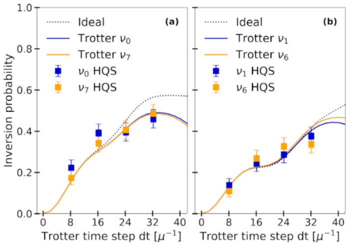

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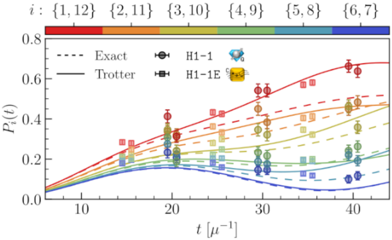

Illa & Savage PRL(2023)

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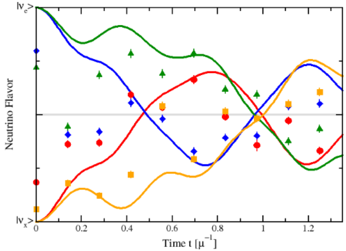

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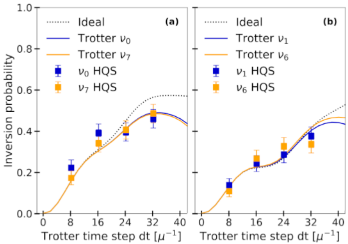

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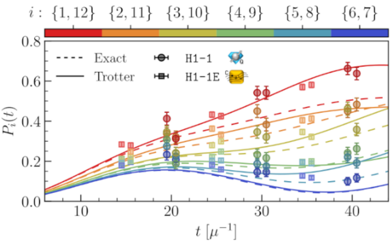

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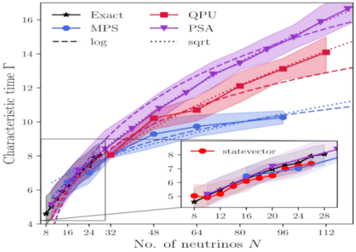
N=112 on IBM (2025)



O.Kiss et al. arXiv:2510.24841

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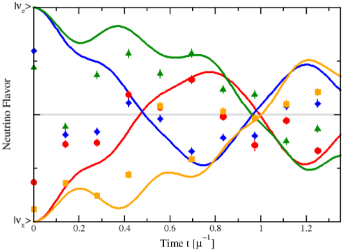
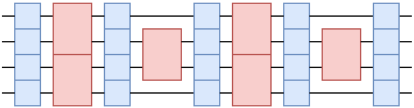


18 CNOT on **4** qubits



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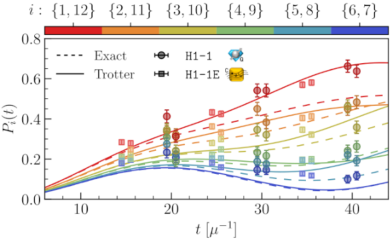

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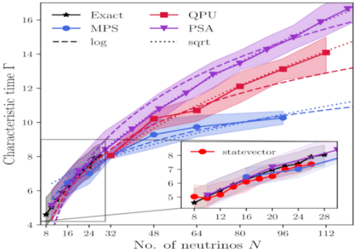

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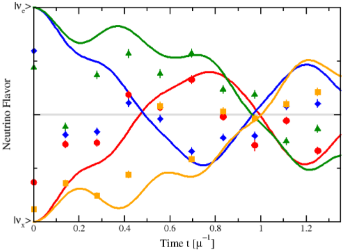

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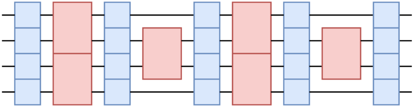
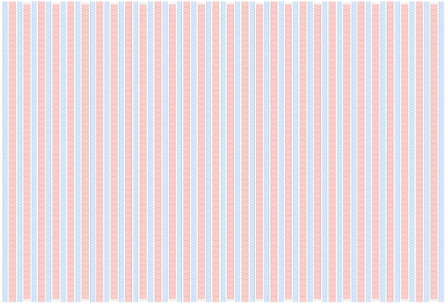


B.Hall et al. PRD(2021)

4995 CNOT on 112 qubits



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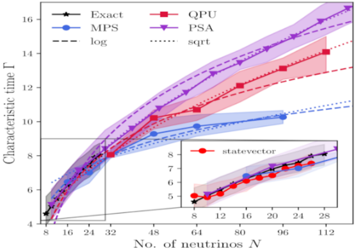

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Nuclear dynamics with quantum (inspired) computing?

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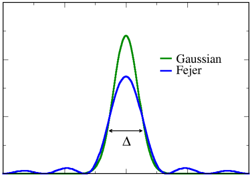
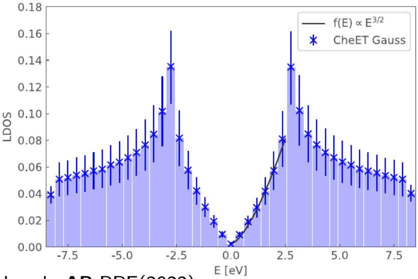
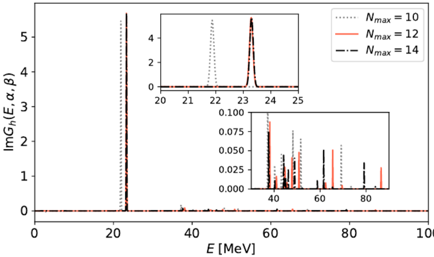


AR & Carlson PRC(2019), **AR** PRA(2020)

- Gaussian approach uses the fact that Chebyshev polynomials can be evaluated efficiently on quantum computers (Berry, Childs, Low, Chuang, . . .)



Sobczyk, **AR** PRE(2022)



Sobczyk, Bacca, Hagen, Papenbrock PRC(2022)

Spin response of bulk neutron matter from CC

Sobczyk & Roggero (2022), Sobczyk, Jiang, Roggero (2025)

With CC we can get a reasonably good approximation of the moments in an efficient way: 5k moments for $N = 114$ particles in ≈ 7k CPU hours

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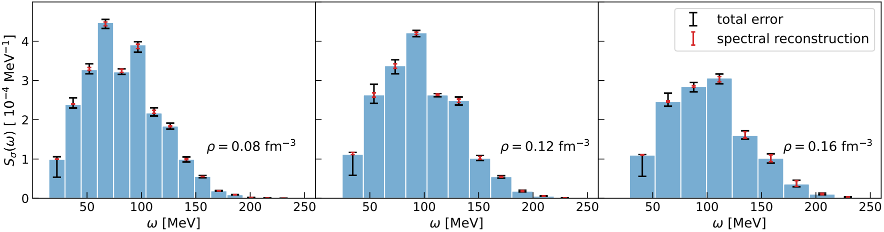

First ab-initio calculation of the frequency dependent spin response of neutron matter with **controllable errors**

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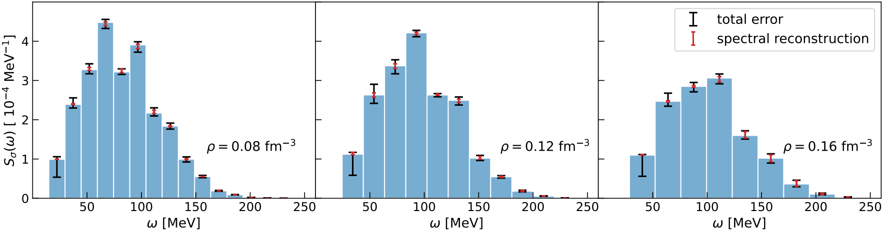


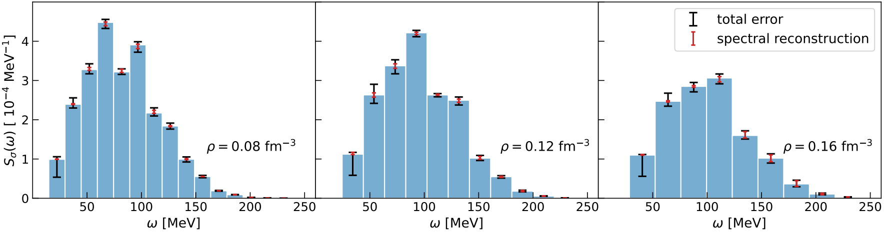
First ab-initio calculation of the frequency dependent spin response of neutron matter with **controllable errors**

TOTAL THEORY ERROR = **MANY-BODY METHOD** + **NUCLEAR INTERACTION** + **FREQUENCY RESPONSE RECONSTRUCTION**

Spin response of bulk neutron matter from CC

Sobczyk & Roggero (2022), Sobczyk, Jiang, Roggero (2025)

With CC we can get a reasonably good approximation of the moments in an efficient way: 5k moments for $N = 114$ particles in $\approx$ 7k CPU hours

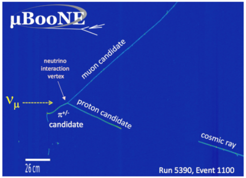


First ab-initio calculation of the frequency dependent spin response of neutron matter with **controllable errors**

TOTAL THEORY ERROR = **MANY-BODY METHOD** + **NUCLEAR INTERACTION** + **FREQUENCY RESPONSE RECONSTRUCTION**

Summary and perspective

- Quantum computing is a strong candidate to considerably improve our simulations of nuclear physics, especially dynamical properties
- Digital quantum devices are constantly getting better at a very fast pace and early fault tolerance might be in sight
- Substantial advances in the last years in the implementation of time evolution for simple nuclear Hamiltonians. Recent results seem to suggest that a **first-quantization** formulation could be advantageous
- More work needed in state preparation and in measurement protocols: what should we measure for **semi-exclusive** scattering processes?
- Classical simulation methods continue to improve also thanks to work on quantum algorithms. Quantum advantage constantly rising bar



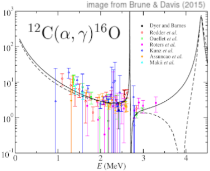
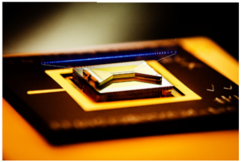



image from Chandra collab.



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Thank you for your attention!